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SHEAR TESTS OF LITESTEEL BEAMS WITH WEB OPENINGS

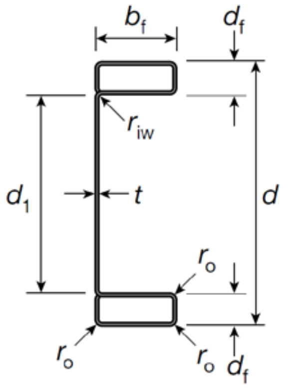
P. KEERTHAN[1], M. MAHENDRAN[2]

[1] *Queensland University of Technology, Brisbane, Qld, <p.keerthan@qut.edu.au>*
[2] *Queensland University of Technology, Brisbane, Qld, <m.mahendran@qut.edu.au>*

ABSTRACT
This paper presents the details of experimental studies on the shear strength of a recently developed, cold-formed steel beam known as LiteSteel Beam (LSB) with web openings. The innovative LSB sections have the beneficial characteristics of torsionally rigid closed rectangular flanges combined with economical fabrication processes from a single strip of high strength steel. They combine the stability of hot-rolled steel sections with the high strength to weight ratio of conventional cold-formed steel sections. The LSB sections are commonly used as flexural members in the building industry. Current practice in flooring systems is to include openings in the web element of floor joists or bearers so that building services can be located within them. Shear behaviour of LSBs with web openings is more complicated while their shear strengths are considerably reduced by the presence of web openings. However, limited research has been undertaken on the shear behaviour and strength of LSBs with web openings. Therefore a detailed experimental study involving 26 shear tests was undertaken to investigate the shear behaviour and strength of different LSB sections. Simply supported test specimens of LSBs with an aspect ratio of 1.5 were loaded at midspan until failure. This paper presents the details of this experimental study and the results. Experimental results showed that the current design rules in cold-formed steel structures design codes (AS/NZS 4600) [1] are very conservative for the shear design of LSBs with web openings. Improved design equations have been proposed for the shear strength of LSBs with web openings based on experimental results from this study.

1. INTRODUCTION

LiteSteel Beam (LSB) is a new cold-formed steel hollow flange channel beam produced by OneSteel Australian Tube Mills (OATM) [2] as shown in Figure 1(a). It is cold-formed using a single strip of high strength steel and a combined cold-forming and Dual Electric Resistance Welding process. The effective distribution of steel material in LSBs results in a very thin and lightweight section with good flexural capacity. The LSB has many applications but, in particular, has become a very popular choice in the flooring systems (see Figure 1 (b)). Current practice in flooring systems is to include openings in the web of floor joists or bearers so that building services can be located within them. Without web openings, services have to be located under the joists leading to increased floor height. This is not an effective use of space and an undesirable result for users. The introduction of web openings in a section significantly reduces its shear capacity due to the reduced web area. The reduction in the primary shear resisting area will lead to a significant reduction in shear capacity. However, the effect of web openings on the flexural capacity is negligible as the web openings are normally located at the centre of web. There are many variables that affect the shear capacity of members containing web openings. They include the shape, position and size of web openings and also the slenderness of the web element. The main aim of this research is to investigate the effect of circular web openings of varying diameters on the shear capacities of different LSB sections using a detailed experimental study. This paper presents the details of a series of shear tests of LSBs with circular web openings, and the results. Experimental shear capacities are compared with the predicted shear capacities using the available design rules, including the current design rules in AS/NZS 4600 [1].



(a) LSB Section

(b) LSB Floor Systems

Figure 1: LiteSteel Beam

2. SHEAR STRENGTH EQUATIONS FOR LSBS

Keerthan and Mahendran [3] proposed new shear strength (τ_v) formulae (Eqs. 1 to 6) for LSBs based on the current design equations for shear strength given in the North American specification (AISI, 2007) [4] using finite element analysis (FEA) and experimental results. The increased shear buckling coefficient given by Equation 7 (k_{LSB}) is included to allow for the additional fixity in the web-flange juncture of LSB. Equations 1 to 3 proposed in [3] also include the available post-buckling strength in shear. The shear capacity in kN can be obtained by multiplying the shear strength (τ_v) by its web area of d_1t_w.

$$\tau_v = \tau_{yw} \quad \text{for} \quad \frac{d_1}{t_w} \le \sqrt{\frac{Ek_{LSB}}{f_{yw}}} \quad \text{(Shear yielding)} \tag{1}$$

$$\tau_v = \tau_i + 0.2(\tau_{yw} - \tau_i) \quad \text{for} \quad \sqrt{\frac{Ek_{LSB}}{f_{yw}}} < \frac{d_1}{t_w} \le 1.508\sqrt{\frac{Ek_{LSB}}{f_{yw}}} \quad \text{(Inelastic shear buckling)} \tag{2}$$

$$\tau_v = \tau_e + 0.2(\tau_{yw} - \tau_e) \quad \frac{d_1}{t_w} > 1.508\sqrt{\frac{Ek_{LSB}}{f_{yw}}} \quad \text{(Elastic shear buckling)} \tag{3}$$

where,

$$\tau_{yw} = 0.6 f_{yw} \tag{4}$$

$$\tau_i = \frac{0.6\sqrt{E k_{LSB} f_{yw}}}{\frac{d_1}{t_w}} \quad (5)$$

$$\tau_e = \frac{0.905 E k_{LSB}}{\left[\frac{d_1}{t_w}\right]^2} \quad (6)$$

For LSBs $k_{LSB} = k_{ss} + 0.87(k_{sf} - k_{ss})$ (7)

Here, t_w = Web thickness, d_1= Clear height of web, f_{yw} = Web yield stress, k_{LSB} = Shear buckling coefficient of LSB, E = Elastic modulus of LSB.

3. EXPERIMENTAL STUDY

Experimental studies were carried out to investigate the shear behaviour of LSBs with web openings using a series of primarily shear tests of simply supported LSBs subjected to a mid-span load (see Figure 2). Two LSB sections were bolted back to back using three T-shaped stiffeners and three web side plates located at the end supports and the loading point in order to eliminate any torsional loading of test beams and possible web crippling of flanges and flange bearing failures. A 30 mm gap was included between the two LSB sections (see Figure 2) to allow the test beams to behave independently while remaining together to resist torsional effects. In order to simulate a primarily shear condition, relatively short test beams were selected based on an aspect ratio (shear span a/ clear web height d_1) of 1.5. Three opening sizes (d_{wh}) of 60, 102 and 127 mm were chosen based on the standard sizes given in OATM [2] for seven of LSB sections, giving a total of 26 shear tests. Table 1 presents the details of the shear test specimens. Figure 2 shows the experimental set-up while Figure 3 shows the shear failure mode of LSB with web openings.

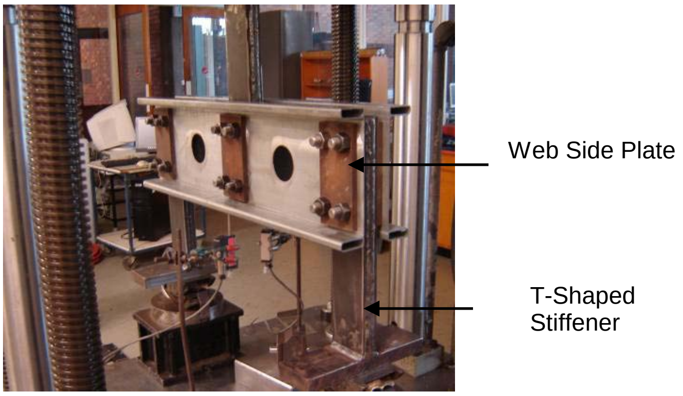


Figure 2: Shear Test Set-up of LSBs with Web Openings

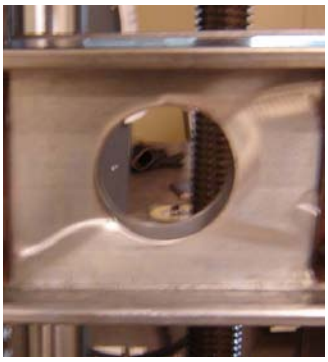


Figure 3: Failure Modes of 200x45x1.6 LSB with 102 mm Web Openings (Aspect Ratio = 1.5)

LSB Section	d_1/t_w	d_{wh} (mm)	d_{wh}/d_1	Exp. Shear Capacity (kN)	q_s (Exp.)	q_s(Eq. 9)	qs(Exp.) / qs (Eq.9)
150x45x1.6	75.9	0	0.00	47.5	1.00	1.00	1.00
	75.9	60	0.50	29.4	0.62	0.66	0.95
	75.9	102	0.85	18.1	0.38	0.41	0.92
150x45x2.0	60.9	0	0.00	59.5	1.00	1.00	1.00
	60.9	60	0.50	42.6	0.72	0.66	1.10
	60.9	102	0.85	28.4	0.48	0.41	1.16
200x45x1.6	105.3	0	0.00	54.2	1.00	1.00	1.00
	105.3	60	0.35	41.4	0.76	0.76	1.00
	105.3	102	0.60	29.1	0.54	0.59	0.92
	105.3	127	0.75	22.2	0.41	0.48	0.85
200x60x2.0	81.2	0	0.00	74.0	1.00	1.00	1.00
	81.2	60	0.38	58.3	0.79	0.74	1.07
	81.2	102	0.64	43.1	0.58	0.56	1.04
	81.2	127	0.79	37.0	0.50	0.46	1.10
250x75x2.5	80.1	0	0.00	118.9	1.00	1.00	1.00
	80.1	60	0.30	104.2	0.88	0.79	1.11
	80.1	102	0.51	>75.0	>0.63	>0.65	>0.97
	80.1	127	0.63	69.1	0.58	0.57	1.03
300x75x2.5	99.6	0	0.00	125.1	1.00	1.00	1.00
	99.6	60	0.24	109.8	0.88	0.83	1.05
	99.6	102	0.41	82.4	0.66	0.72	0.92
	99.6	127	0.51	>75.0	>0.60	>0.65	>0.93
300x75x3.0	87.4	0	0.00	Not Available	1.00	1.00	1.00
	87.4	60	0.24	>120.0	NA	0.83	NA
	87.4	102	0.41	112.1	NA	0.72	NA
	87.4	127	0.51	92.0	NA	0.65	NA

Table 1: Shear Capacity Reduction Factor for LSBs with Web Openings

4. PROPOSED EQUATIONS FOR THE SHEAR CAPACITY OF LSBS WITH WEB OPENINGS

It is proposed that the shear capacity of LSB with web openings (V_{nl}) can be calculated using a reduction factor q_s applied to the shear capacity of LSBs without web openings (V_v = τ_v from Eqs.1-3 x d_1t_w). The new shear capacity equations for LSBs without web openings are discussed in Section 2. Equations 8 and 9 show the proposed design equations for the shear capacity of LSBs with web openings **(V_{nl}).**

$$V_{nl} = q_s V_v \qquad \text{for} \qquad 0.24 \le \frac{d_{wh}}{d_1} \le 0.85 \tag{8}$$

$$q_s = 1 - \frac{d_{wh}}{1.45 d_1} \tag{9}$$

where d_{wh} = depth of web openings

Table 1 shows the ultimate shear capacities of LSBs with web openings from tests, and the shear capacity reduction factor q_s calculated as V_{nl}/V_v for varying ratios of depth of web openings to clear height of web (d_{wh}/d_1).

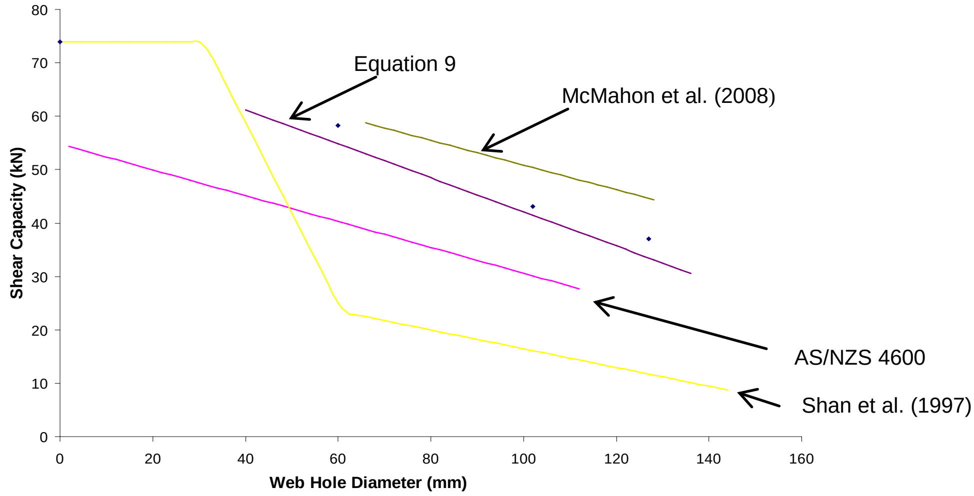


Figure 4: Shear Capacity versus Depth of Web Opening
(200x60x2.0 LSB, Aspect Ratio = 1.5)

5. COMPARISON OF SHEAR CAPACITY REDUCTION FACTORS FROM EXPERIMENTS AND EQUATION 9

In order to assess the accuracy of the proposed design equations for the shear capacity of LSBs with web openings (Eq. 9), their predictions are compared with the experimental shear capacity reduction factors in Table 1. It shows that the shear capacity reduction factor predicted by Equation 9 agrees well with the experimental shear capacity reduction factor. The mean value of test to predicted shear capacity reduction factor ratio is 1.00 while the corresponding coefficient of variation (COV) is 0.073. However, it was found that the proposed design equation (Equation 9) is slightly unconservative when the LSBs have large web openings (Table 1).

Other design equations are available for the shear capacity reduction factor (**q_s**) for cold-formed steel beams in shear [1,5,6]. Some of them are shown next.

$$q_s = 1 - \frac{d_{wh}}{2d_1} \quad \text{for} \quad 0.4 \le \frac{d_{wh}}{d_1} \le 0.8 \qquad \text{McMahon et al. [5]} \tag{10}$$

$$q_s = 1.51 \times 10^{[-1.33(d_{wh}/d_1)]} \quad \text{for } 0 \le \frac{d_{wh}}{d_1} \le 1.0 \quad q_s \le 1 \quad \text{Shan et al. [6]} \tag{11}$$

AS/NZS 4600 [1]:

$$q_s = 1 \quad \text{for} \quad \frac{c}{t_w} > 54 \tag{12a}$$

$$q_s = \frac{c}{54 t_w} \quad \text{for } 5 \le \frac{c}{t_w} < 54 \tag{12b}$$

$$c = \frac{d_1}{2} - \frac{d_{wh}}{2.83} \quad \text{for circular web openings} \tag{12c}$$

Comparison of shear capacity reduction factors from experiments given in Table 1 and those predicted by the above equations (Eqs. 10 to 12) gave either over-conservative or unsafe results. Figure 4 plotted as shear capacity versus the depth of web opening confirms this observation in the case of one LSB section (200x60x2.0LSB). It shows that McMahon et al.'s [5] design equation is unconservative for the shear capacity of LSBs with web openings while those in AS/NZS 4600 [1] and Shan et al. (1997) [6] are very conservative for the shear capacity of LSBs with web openings.

6. CONCLUSIONS

This paper has presented the details of an experimental investigation into the shear behaviour of LSBs with web openings. Twenty six shear tests were undertaken using a three point loading arrangement. Comparison of ultimate shear capacities from tests showed that AS/NZS 4600 [1] design equations are conservative for the shear design of LSBs with web openings. It was found that McMahon et al.'s [5] design equation is unconservative while Shan et al.'s [6] design equations are too conservative for the shear capacity of LSBs with web openings. Appropriate improvements have been proposed in the form of modified shear capacity reduction factors to determine the shear capacity of LSBs with web openings based on experimental results.

7. ACKNOWLEDGEMENTS

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